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The contribution of China's bilateral trade to global carbon emissions in the context of globalization

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ABSTRACT

Controlling and reducing carbon emissions for mitigation of climate change are a global common consensus. It is imperative for legitimately and effectively ascertaining responsibilities among countries to study CO_2 emissions embodied in the international trade. As the largest exporter and the second largest importer in the world, the large amount of CO_2 emissions embodied in China's bilateral trade have a significant impact on China's and global carbon emissions. Based on the single region input-output tables using the non-competitive imports assumption, this study estimated CO_2 emissions embodied in China's bilateral trade with 219 countries/regions over the period of 2000–2014, and analyzed the contribution of China's bilateral trade to global carbon emissions under the assumption of non-trade scenario. The results show that, CO_2 emissions embodied in China's exports and imports in 2014 were 2561.1 Mt and 1209.9 Mt respectively, and CO_2 emissions embodied in exports were higher than those in imports throughout the period. It is indicated that China had produced a large amount of CO_2 emissions for other countries through the international trade. And meanwhile, China avoided a large amount of CO_2 emissions with the rapid growth of imports. And furthermore, the net CO_2 emissions embodied in China's bilateral trade had been declining since 2011. At last, China's bilateral trade had extremely little impact on global carbon emissions. It is concluded that there is a possibility of reducing global carbon emissions based on the results of China's bilateral trade with countries along the routes of Silk Road Economic Belt and 21st-Century Maritime Silk Road.

1. Introduction

As the world's largest emitter, China alone produced 9040.7 Mt carbon dioxide (CO_2) emissions from energy activities in 2015 and it was responsible for 28.0% of global CO_2 emissions (International Energy Agency (IEA), 2017). Under the pressure of global emission reduction and international responsibilities, China submitted the Intended Nationally Determined Contribution (INDC) in June 2015: to achieve the peaking of carbon dioxide emissions around 2030 and make best efforts to peak early; and to lower CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level by 2030 (National Development and Reform Commission (NDRC), 2015). The United Nations Framework Convention on Climate Change (UNFCCC) requires that countries are responsible for the CO_2 emissions emitted from all productive activities within their national geographic borders. Most CO_2 emission estimations are studied on the basis of a production-based accounting approach. The approach makes carbon constraint nations reduce their greenhouse gas inventories by importing goods from other countries with looser environmental standards. The increasing of CO_2 emissions embodied in international trade is the main reason why CO_2 emissions of developed countries increased with a relatively lower growth while CO_2 emissions of developing countries increased sharply (Weber et al., 2008; Nakano et al., 2009). In this situation, global CO_2 emissions are likely to continue to increase rather than decrease (Wyckoff and Roop, 1994; Ahmad and Wyckoff, 2003; López et al., 2018). In recent years, some scholars suggested that considering another consumption-based accounting approach may be conducive to promoting international climate change negotiations and equitable distribution of carbon emission reduction tasks (Pan et al., 2008; Peters, 2008; Peters and Hertwich, 2008a; Peters and Hertwich, 2008b). The IPCC fifth climate change assessment report also carried out a special discussion of consumption-based CO_2 emissions accounting method (Intergovernmental Panel on Climate Change (IPCC), 2014). In the context of globalization, CO_2 emissions embodied in international trade have become a key

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factor influencing the fairness of CO_2 emission reduction responsibility between the above two accounting approaches. The impact of international trade should not be ignored when China takes the CO_2 emission reduction responsibility, assigns reduction tasks and achieves carbon reduction targets.

China formally joined the World Trade Organization (WTO) in 2001, and then participated in international competition and cooperation in a broader magnitude. International trade has become the main driving force for China's rapid economic development. According to the UN Comtrade Database statistics, the volume of China's merchandise exports has reached USD 2134.5 billion in 2016, taking account in 13.5% of global exports (United Nations Statistics Division (UNSD), 2016). China produced large amounts of CO_2 emissions embodied in exports consumed in other countries at the cost of China's own energy consumption and environmental pollution. The value of China's merchandise imports has reached USD 1589.9 billion in 2016, and the trade structure of imports was significantly different from that of exports. Both volumes of crude oil and iron ores represented 10.9% of China's merchandise imports in that year (Department of Economic and Social Affairs Statistics Division (DESA), 2016). China has avoided many CO_2 emissions by increasing imports of energy and mineral resources with high carbon intensity while those exporters might release more CO_2 emissions due to the trade. By estimating CO_2 emissions embodied in China's exports and imports, it could make clear whether international trade made China undertake CO_2 emissions for other countries or avoid more CO_2 emissions, and further study the role of international trade in China's CO_2 emission reduction. In recent years, Brexit, USA withdrawing from the Trans-Pacific Partnership and the rising trade protectionism brought uncertainties to the development of international trade. To seek the development of China itself and the neighboring regions, China proposed the initiative of Silk Road Economic Belt and 21 st-Century Maritime Silk Road (B&R) in 2015. The B&R initiative follows the trend of economic globalization and it is to share China's development opportunities with countries along the routes and achieve common prosperity. With the further promotion and enhancement of the B&R initiative, the location distribution and industrial structure of China's international trade will change in the future, and the characteristic of CO_2 emissions embodied in China's international trade will be different. At this point, we calculate CO_2 emissions embodied in China's international trade and analyzes the contribution of China's international trade to global CO_2 emissions from the perspective of deglobalization, which both have certain research value and theoretical significance.

2. Literature review

The accumulated CO_2 emissions emitted in the production of the product are said to be "embodied" CO_2 emissions (Peters, 2008). CO_2 emissions embodied in trade are generally estimated by using emission relevant energy consumption in the production of export and import goods and services. The most common methodology for embodied CO_2 emission estimates is input-output analysis (IOA) (Leontief, 1970). According to the scale of input-output tables, there are two main approaches: the single-region input-output (SRIO) model and the multi-region input-output (MRIO) model. Critical distinctions between the two models can be made with regards to the treatment of the imported intermediate goods, assumption about technology and model complexity.

The SRIO model takes a single country and estimates CO_2 emissions embodied in its total trade with the rest of the world (ROW). However, the treatments of imports in the SRIO model are different. Two approaches can be found to deal with a country's imports. The competitive imports assumption refers to the same productive technology between the imported products and those produced domestically. The IO table using the competitive imports assumption does not distinguish imported products from the intermediate use or final use. The IO table using the non-competitive imports assumption treats the imported products as different from the domestic ones and tabulates them separately. The corresponding CO_2 emissions embodied in these imports are estimated using their origins based on the non-competitive imports assumption. A large number of embodied CO_2 emission studies use the SRIO model because of the simplicity of the model and its lower data requirement and easier calculation (Wiedmann et al., 2007; Sato, 2014). There are some typical studies of China's embodied CO_2 emissions using the competitive imports assumption, such as Chen and Zhang (2010), Li and Qi (2010), Lin and Sun (2010), Yan and Yang (2010), Xu et al. (2011). In recent years, more and more studies adopted the SRIO model with non-competitive imports (Su and Ang, 2010; Su et al., 2010; Wei et al., 2011; Dietzenbacher et al., 2012; Liu et al., 2013; Jiang et al., 2015; Liu et al., 2017). Su and Ang (2013) found that embodied CO_2 emissions obtained using the competitive imports assumption approach are higher by around 25–45% than those with the non-competitive imports assumption approach on the premise of the same basic data. It is generally considered unreasonable neglecting the impact of imports in production processes during the calculation of CO_2 emissions embodied in exports (EEX). However, due to the lack of emission data for imported products in SRIO model, several researches assumed the same emission intensity for both imports and China's domestic products to calculate emissions avoided by imports (EAI) (Weber et al., 2008; Chen and Zhang, 2010; Lin and Sun, 2010). This substitution would overrate China's CO_2 emissions embodied within import products (EEI) because China have higher emission intensity than most of its importers. Some researches adopted the emission intensity of one typical importer or the (weighted) average value of several importers to estimate China's EEI (Yan and Yang, 2010; Wei et al., 2011; Liu et al., 2013). And other studies calculated the EEI using input coefficients and emission intensities of China's importers where the imported goods and services are produced (Pan et al., 2008; Jiang et al., 2015; and Liu et al., 2017). These studies improved the estimation accuracy of China's EEI. In addition, all China's official input-output tables use the competitive imports assumption. Some researchers derived China's non-competitive (imports) input-output tables using the domestic production technology matrix (Pan et al., 2008; Su et al., 2010; Su and Ang, 2010; Wei et al., 2011; Liu et al., 2013; Su and Ang, 2013). But the same proportion of imported products in intermediate use and final use would introduce uncertainty in the embodied CO_2 emission estimation.

Limited to the lack of the trade data between China and global partners, SRIO models are rarely used to globally discuss China's CO_2 emissions embodied in the international trade. The MRIO model represents the interactions among industrial sectors within an economy and provides the spatial linkages of industries between regions based on a more complex data foundation compared to the SRIO model. By employing the MRIO model, a rapidly growing body of literature has been created in recent years that estimates emissions embodied in global trade and consumption-based CO_2 emissions (Sato, 2014; Wiedmann, 2009). Ahmad and Wyckoff (2003), and Nakano et al. (2009) measured embodied CO_2 emissions of 24 and 41 countries/regions using MRIO tables and other data of OECD database. Peters et al. (2011) and Atkinson et al. (2011) determined CO_2 emissions embodied in international trade among 113 and 15 countries/regions using the data provided by Global Trade Analysis Project (GTAP). Zhang et al. (2017) and López et al. (2018) adopted MRIO tables from the WIOD database to make an analysis on the pollution haven hypothesis. In the MRIO model, the exogenous demand is always the final use with the domestic

and imported intermediate use determined endogenously, and CO_2 emissions embodied in imports are allocated to the final consumers (Peters, 2008; Sinden et al., 2011; Su and Ang, 2011). MRIO models diffuse responsibility among agents of different countries participating in global value chains because the inputs are part of global chains of production until they are finally destined to attend to final demand (Atkinson et al., 2011).

A bilateral trade input-output model (BTIO) exhibit fewer potential inaccuracies compared with MRIO models (Atkinson et al., 2011), and in particular, BTIO models are considered preferable for monitoring bilateral emission trade balances (Guo et al., 2010; Edens et al., 2011; Wu et al., 2016), explaining "weak carbon leakage" (Peters and Hertwich, 2008a) and testing the pollution haven hypothesis (Cadarso et al., 2018). The emission boundary of the BTIO model (also labelled emissions embodied in bilateral trade, EEBT) is directly comparable to the original statistical source, and therefore the trade data treating process is simplified and transparent (Peters, 2008; Sato, 2014) which makes it arguably better for analysis of trade and climate policy (Peters, 2008; Edens et al., 2011). The BTIO model does not differentiate whether imports are used for intermediate use or final use. All imports are allocated to the country which produces them according to the criteria of producer responsibility, and the EEI is estimated by using their relevant data in order to avoid the uncertainty associated with SRIO models. Although the treatment of undistinguishing intermediate use or final use in trade is arguable, some recent studies estimated the emissions embodied in bilateral trade between China and other countries. Shui and Harriss (2006), Guo et al. (2010) and Du et al. (2011) estimated CO_2 emissions embodied in China-USA international trade. Tan et al. (2013) and Jayanthakumaran and Liu et al. (2016) quantified CO_2 emissions embodied in China-Australia international trade. Li and Hewitt (2008), Wu et al. (2016) and Yu and Chen (2017) estimated the amount of CO_2 emissions embodied in the bilateral trade between China and the UK, Japan and South Korea, respectively. These results generally indicated that CO_2 emissions embodied in China's exports were higher than those embodied in China's imports.

MRIO models cover multiple countries/regions on the basis of global scale, however, the research object of those studies referring to MRIO models is generally restricted to the region coverage of MRIO modelling. By comparison, there are more flexibility for BTIO models which only need SRIO tables of their research objects. Moreover, MRIO models are not possible to know if international trade increases or decreases global carbon emissions because the aggregation of worldwide trade and emissions balances for all countries is always zero (López et al., 2013). Based on the BTIO model, several researches conducted a hypothetical non-trade scenario analysis (Shui and Harriss, 2006; Tan et al., 2013; Jayanthakumaran and Liu et al., 2016; Yu and Chen, 2017). Contrary to the concept of economic globalization, the non-trade scenario assumes that there is no import or export between countries/regions, and all products are produced domestically. The impact of international trade on the global CO_2 emissions can be quantified under the assumption of non-trade scenario.

This paper intends to quantitatively calculate CO_2 emissions embodied in the bilateral trade between China and all its 219 trade partners based on the BTIO model with the SRIO tables using the non-competitive imports assumption provided by the World Input-Output Database and other relevant energy and environmental data. The time span is from 2000 to 2014. The change of China's embodied CO_2 emissions is analyzed from the perspective of location distribution and structural adjustment, combining the comparative analysis of the 38 basic countries and 68 countries along the B&R routes. The contribution of China's bilateral trade to the global carbon emissions is also quantitatively calculated and discussed based on the EEBT model with the assumption of non-trade scenario.

3. Methods

The standard SRIO model with the competitive imports assumption can be formulated as:

$$x = (I - A)^{-1} y \tag{1}$$

where x is the column vector of total output; I is the identity matrix; A is the matrix of direct requirement coefficient, demonstrating the relationship of each sector; and y is the column vector of final use including final consumption, gross capital formation and exports.

The SRIO model with the non-competitive imports assumption takes imports off from intermediate use and final use, and it can be formulated as:

$$x = (I - A^d)^{-1} y^d \tag{2}$$

where A^d is the matrix of domestic direct requirement coefficient; and y^d is the vector of domestic final use and exports.

CO_2 emissions from y^d can be formulated from Eq. (2) as:

$$CO_2 = fE(I - A^d)^{-1} y^d \tag{3}$$

where f is the row vector of emission factor representing CO_2 emissions per unit of energy consumption; and E is the energy intensity matrix representing the energy consumption per unit of the output value.

3.1. CO_2 emissions embodied in exports

As a part of final use Y^d, the production process of exports occurs domestically in China. By using the CO_2 emission estimating model in Eq. (3), it is easy to formulate China's EEX as:

$$EEX_i = f^{CH} E^{CH} (I - A^{d,CH})^{-1} y_i^x \tag{4}$$

where EEX_i is CO_2 emissions embodied in China's exports to region i, including direct and indirect CO_2 emissions; f^{CH} is the $1 \times m$ vector of CO_2 emission factor, m represents energy type; E^{CH} is the $m \times n$ energy intensity matrix representing China's energy consumption per unit of output value, n represents industrial sector in the input-output table; $(I\text{-}A^{d,CH})^{-1}$ is the China's domestic Leontief inverse matrix in the SRIO table with non-the competitive imports assumption; ${y^x}_i$ is the vector of China's exports (intermediate and final products) to region i. When the vector ${y^x}_i$ is diagonalized to the matrix ${\hat{y}^x}_i$, CO_2 emissions embodied in each sector of China's exports can be estimated individually.

3.2. CO_2 emissions embodied in imports

In the BTIO model, the EEI is calculated with data of corresponding regions who China imports from, and the EEI is regarded as the EEX of those regions. China's EEI from region i can be formulated as:

$$EEI_i = f_i^{IM} E_i^{IM} (I - A_i^{d,IM})^{-1} y_i^m \tag{5}$$

where EEI_i is CO_2 emissions embodied in China's imports from region i; f_i^{IM} represents CO_2 emission factor of region i; ${E_i}^{IM}$ is the energy intensity matrix of region i; $(I\text{-}{A_i}^{d,IM})^{-1}$ is the domestic Leontief inverse matrix of region i; ${y^m}_i$ is the vector of China's imports(intermediate and final products) from region i.

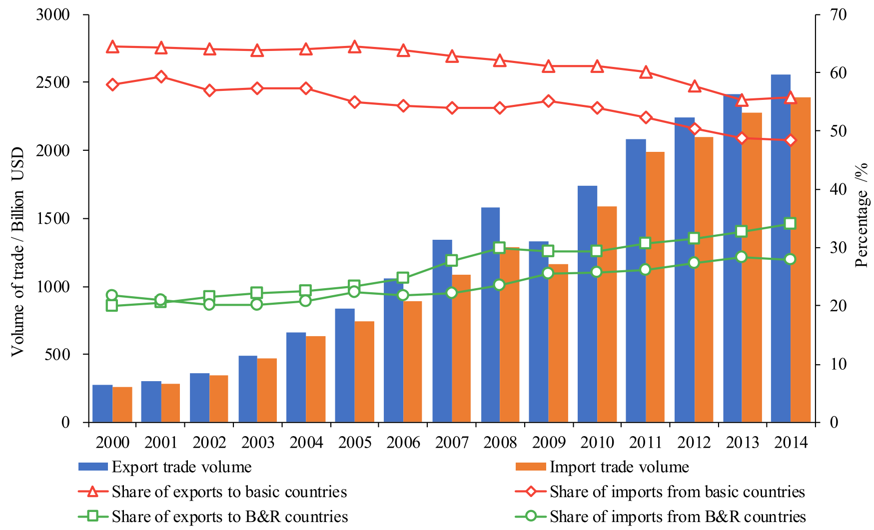

Fig. 1. China's bilateral trade from 2000 to 2014.

3.3. Net CO_2 emissions embodied in bilateral trade

The net CO_2 emissions embodied in bilateral trade (NEEBT) between China and region i equals to EEX from China to region i minus EEI from region i to China and can be calculated in Eq. (6).

$$NEEBT_i = EEX_i - EEI_i \tag{6}$$

The total NEEBT of China can be estimated based on relevant data of China and all its trade partners:

$$NEEBT = EEX - EEI = \sum_i EEX_i - \sum_i EEI_i \tag{7}$$

3.4. Contribution of bilateral trade to global CO_2 emissions

We adopt the non-trade scenario to calculate the contribution of China's bilateral trade to global CO_2 emissions following Shui and Harriss (2006), Tan et al. (2013), Jayanthakumaran and Liu (2016) and Yu and Chen (2017). According to the production-based accounting approach (like the Kyoto protocol), producers should be responsible for CO_2 emissions embodied in the international trade within their own territory. Therefore, many countries import goods from China instead of producing them domestically and reduce their CO_2 emissions by the consumption of imported goods. But under the assumption of non-trade scenario, all China's exports are assumed to be produced by the region importing them, and the resulting CO_2 emissions can be calculated in Eq. (8).

$$EEX^{INV} = \sum_i EEX_i^{INV} = \sum_i \left(f_i^{IM} E_i^{IM} (I - A_i^{d,IM})^{-1} y_i^x \right) \tag{8}$$

where EEX^{INV} denotes CO_2 emissions of region i when they produce their imports $y^x{}_i$ from China; other parameters except $y^x{}_i$ are the data of region i.

We consider the difference of actual CO_2 emissions embodied in China's exports and those in the non-trade scenario to be the impact of China's export trade on global CO_2 emissions (IEGE). Thus, it can be formulated as follows:

$$IEGE = EEX - EEX^{INV} \tag{9}$$

On the other hand, China also imports goods from other regions to reduce its domestic CO_2 emissions. Assuming all these imports are produced in China, the resulting CO_2 emissions can be calculated in Eq. (10).

$$EEI^{INV} = \sum_i EEI_i^{INV} = f^{CH} E^{CH} (I - A^{d,CH})^{-1} \sum_i y_i^m \tag{10}$$

where EEI^{INV} represents the amount of CO_2 emissions of $y^m{}_i$ if that had been produced in China rather than imported from region i.

Likewise, the impact of China's import trade on global CO_2 emissions (IIGE) is thus calculated as follows:

$$IIGE = EEI - EEI^{INV} \tag{11}$$

The impact of China's bilateral trade on global CO_2 emissions (IBTGE) can be quantified by the sum of the two impacts above, as $IBTGE$=$IEGE$+$IIGE$. When $IBTGE > 0$, the contribution of China's bilateral trade to global CO_2 emissions is positive. It is indicated that China's bilateral trade increases global CO_2 emissions. When $IBTGE < 0$, China's bilateral trade reduces global CO_2 emissions. And when $IBTGE = 0$, China's bilateral trade makes no difference to global CO_2 emissions.

4. Data sources and processing

The SRIO tables using the non-competitive imports assumption from 2000 to 2014 are derived from World Input-Output Database (WIOD) (Timmer et al., 2015). The database contains 38 countries[1] besides China and Taiwan. These 38 countries are defined as "basic countries" in this paper because they have complete SRIO tables. CO_2 emissions and relevant energy use of these countries from 2000 to 2009 are also provided in WIOD. The energy use from 2010 and 2014 are derived from Energy Statistics Database oftions Statistics Division (United Nations Statistics Division (UNSD), 2017). The corresponding CO_2 emissions are obtained by applying CO_2 emission factors adopted from Intergovernmental Panel on Climate Change (IPCC), 2006 to the energy consumption. The data of goods in China's bilateral exports and imports in the form of 4-digit Harmonized System (HS) code is derived from UN Comtrade Database of United Nations Statistics Division (UNSD), 2016, including 219 trade partners (countries or regions). Imports are in Cost Insurance Freight (CIF) prices, and exports are in producer prices. The data of services is compiled from UN Comtrade Database, while taking into account Organization for Economic Co-operation and Development (OECD), 2017. There is a lack of re-export trade data in UN Com-

[1] 38 countries include (A-Z) Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Republic of Korea, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, Poland, Portugal, Romania, Russia, Slovak Republic, Slovenia, Spain, Sweden, Turkey, United Kingdom and United States

Table 1
Industrial sectors of China's trade.

Code	Sector	Code	Sector
S01	Agriculture	S11	Basic Metals and Fabricated Metal Products
S02	Mining	S12	Machinery
S03	Food, Beverages and Tobacco Products	S13	Electronic and Electrical Equipment
S04	Textiles, Wearing Apparel and Leather Products	S14	Transport Equipment
S05	Wood Products	S15	Other Manufacturing and Recycling
S06	Paper Products and Printing	S16	Electricity, Gas and Water supply
S07	Coke and Refined Petroleum Products	S17	Construction
S08	Chemical Products	S18	Travel and Transport
S09	Rubber and Plastics	S19	Other Services
S10	Other Non-metallic Mineral Products		

Table 2
Emission relevant energy types.

Energy types				
Hard coal	Brown coal	Coke	Crude oil	Diesel
Gasoline	Jet fuel	Light fuel oil	Heavy fuel oil	Naphtha
Other petroleum	Natural gas	Other gas	Waste	

trade Database. Adopting the method of Guo et al. (2010) (Guo et al., 2010), CO_2 emissions caused by re-export trade are not considered in the accounting framework because the volume of re-export goods is small compared to the total. In other words, all China's imports are produced in those regions who China imports from, and exports are produced domestically by China's own products.

The 38 basic countries include 27 European countries, 6 Asian countries, 4 American countries and 1 Oceanian country. ROW representing the rest of the world contains the other 181 countries/regions. Due to the lack of essential data of ROW, the EEI is estimated based on the typical region substitution method, in which SRIO tables, energy intensities and CO_2 emission factors of the typical regions are substituted for those parameters of ROW. The typical regions are selected from basic countries, and their average data are used for substitution. Europe contains many basic countries, and thus its typical regions are Spain and Greece whose production technology is equivalent to the average level of Europe. There are 6 Asian countries, only 1 Oceanian country and no African countries in the 38 basic countries, but there are 120 Asian, Oceanian and African (AOA) countries/regions in ROW. The selecting principle of typical regions is the priority of developing countries in each continent except for the only country – Australia in Oceania. Therefore, the AOA regions in ROW share the four selected typical regions – Australia, India, Indonesia and Turkey. Both Mexico and Brazil are substituted for the rest of American regions.

According to the data coverage of WIOD, there are 35 sectors and 26 energy types. In this paper, the trade industries are combined to 19 categories in accordance with the industrial sectors of China's bilateral trade. And there are 14 types of energy actually generated CO_2 emissions. The industrial sectors and energy types are detailed in Table 1 and 2.

5. Results

5.1. Descriptive overview of China's bilateral trade

Since joining the WTO, China's bilateral trade has rapidly grown. China's bilateral trade from 2000 to 2014 is shown in Fig. 1. The volume of exports increased from USD 279.6 billion in 2000 to USD 1577.8 billion in 2008 with an average annual growth rate of 24.8%. Meanwhile, the volume of imports increased from USD 279.6 billion to USD 1291.7 billion, and the net export peaked at USD 286.1 billion in 2008. After a marked decline in 2009 affected by the financial crisis, China's bilateral trade resumed its growth after 2010, and moreover the growth rate of imports was higher than exports. China's exports and imports reached USD 2561.5 billion and 2390.8 billion in 2014, accounting for 9.8% and 9.4% of the world as the largest exporter and the second largest importer. The percentages of China's exports to 38 basic countries were higher than those of imports. The former ranged between 55% and 65% while the latter ranged between 48% and 60%, and both had declined in varying degrees since 2010. The volume of bilateral trade between China and B&R countries[2] showed a growing trend during the period. The percentage of China's exports to B&R countries increased from 20.0% in 2000 to 34.0% in 2014, and imports also increased from 21.8% to 28.0%. It is indicated that the location distribution of China's international trade is gradually transferring to the its neighboring regions.

5.2. CO_2 emissions embodied in exports

Fig. 2 shows CO_2 emissions embodied in China's exports from 2000 to 2014 that were obtained using Eq. (4). The total EEX showed the trend of rapid growth in the early stage before 2008, increasing from 576.7 Mt (19.9% of China's production-based CO_2 emissions in 2000) to 1758.4 Mt (31.8% of China's production-based CO_2 emissions in 2007). After two consecutive years of decline, the EEX substantially increased to 2374.2 Mt (25.6%) in 2010. The EEX tended to be stable after 2011 and resulted in 2562.7 Mt (23.1%) in 2014. China's export volume grew 8.2 times during 2000–2014, whereas the EEX had a growth of 3.4 times much lower than the export volume. The growing exports did not lead to an overgrowth of EEX after 2011 because of the sharply declined CO_2 emission intensity that was benefited from China's enforcement of energy conservation and emission reduction policies. The share of EEX to basic countries maintained at around 60%–65% before 2011 and decreased from 60.6% in 2011 to 55.7% in 2014. Mi et al. (2017) also found that the destinations of China's EEX have partially shifted from developed countries to developing countries and energy efficiency gains effectively offset China's EEX. Due to the limited growth of exports to basic countries as mentioned above, the EEX to basic countries could be predicted to decrease with the improved energy efficiency in near future. The EEX to B&R countries had a significant growth during the period, and meanwhile its proportion increased from 20.4% to 35.8%. With the gradual promotion of the B&R initiative, China's exports to the countries along

[2] 68 B&R countries include (A-Z) Afghanistan, Albania, Armenia, Azerbaijan, Bahrain, Bangladesh, Belarus, Bhutan, Bosnia and Herzegovina, Brunei Darussalam, Bulgaria, Cambodia, Croatia, Czech Republic, Egypt, Estonia, Ethiopia, Georgia, Hungary, India, Indonesia, Iran, Iraq, Israel, Jordan, Kazakhstan, Korea, Kuwait, Kyrgyzstan, Lao People's Dem. Rep., Latvia, Lebanon, Lithuania, Macedonia, Malaysia, Maldives, Moldova, Mongolia, Montenegro, Myanmar, Nepal, New Zealand, Oman, Pakistan, Palestine, Philippines, Poland, Qatar, Romania, Russia, Saudi Arabia, Serbia, Singapore, Slovak, Slovenia, South Africa, Sri Lanka, Syrian, Tajikistan, Thailand, Timor-Leste, Turkey, Turkmenistan, Ukraine, United Arab Emirates, Uzbekistan, Vietnam and Yemen

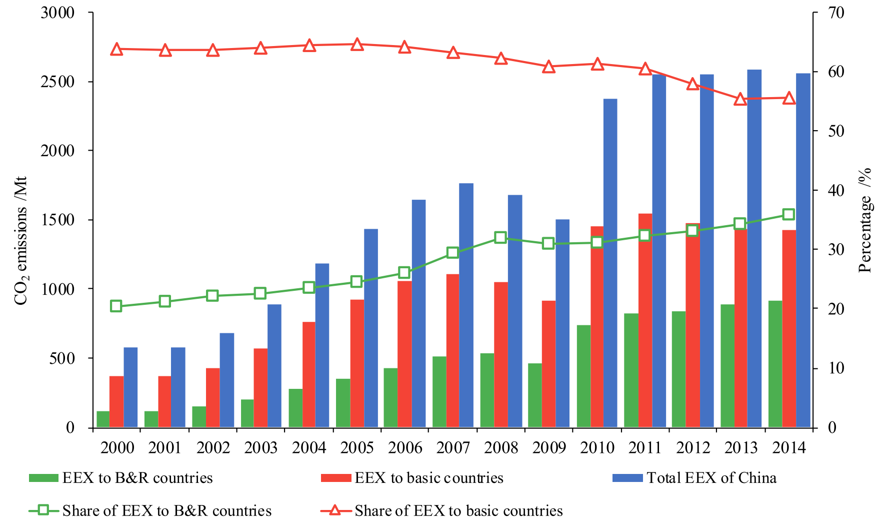

Fig. 2. CO_2 emissions embodied in China's exports from 2000 to 2014.

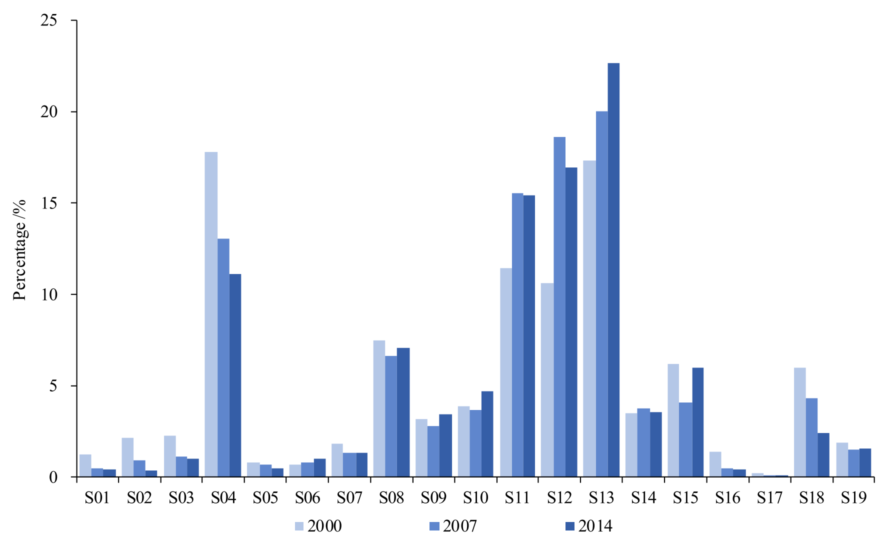

Fig. 3. Industrial structure of CO_2 emissions embodied in China's exports.

the routes will increase, and the consequent increase of EEX will occur.

Fig. 3 shows the industrial structure of CO_2 emissions embodied in China's exports in 2000, 2007 and 2014. The sector codes are listed in Table 1. The EEX was mainly concentrated in four sectors: Textiles, Wearing Apparel and Leather Products (S04), Basic Metals and Fabricated Metal Products (S11), Machinery (S12) and Electronic and Electrical Equipment (S13). In 2014, Electronic and Electrical Equipment (S13) had the largest EEX (580.9 Mt) of all sectors, followed by Machinery (S12, 433.7 Mt), Basic Metals and Fabricated Metal Products (S11, 395.7 Mt) and Textiles, Wearing Apparel and Leather Products (S04, 284.4 Mt). Together, the top four sectors accounted for 66.1% of the total EEX of China. The industrial structure of the EEX changed greatly during the period. Textiles, Wearing Apparel and Leather Products (S04) had the largest proportion (17.8%) of EEX in 2010, and after a continuous decline, it just accounted for 11.1% in 2014. Besides, the proportion of some other sectors also declined obviously, such as several primary product industries: Agriculture (S01), Mining (S02), Food, Beverages and Tobacco Products (S03), Wood Products (S05) and Travel and Transport (S18). For Basic Metals and Fabricated Metal Products (S11), Machinery (S12) and Electronic and Electrical Equipment (S13), the proportions of their EEX increased significantly from 11.5%, 10.6% and 17.4% in 2000 to 15.4%, 16.9% and 22.7%, respectively. The proportions of resource-intensive and labor-intensive sectors are decreased gradually due to the change of China's export structure. More EEX is concentrated in certain capital-intensive and technology-intensive manufacturing industries. Precisely because of the continuous progress of production technology and improvement of energy efficiency in most of manufacturing industries, the EEX began to stagnate though China's exports still increased rapidly in recent years.

5.3. CO_2 emissions embodied in imports

CO_2 emissions embodied in China's exports from 2000 to 2014 are shown in Fig. 4. As we estimated, the total EEI increased from 230.4 Mt (8.0% of China's production-based CO_2 emissions in 2000) to 1210.5 Mt (10.9% of China's production-based CO_2 emission in 2014). The average annual growth rate was 12.6%, higher than that of EEX (11.2%). Different to the stable EEX after 2011, the EEI still kept a rapid growth. China avoided a large amount of production-based CO_2 emissions by importing more and more goods instead of producing them domestically. The change of EEI from basic coun-

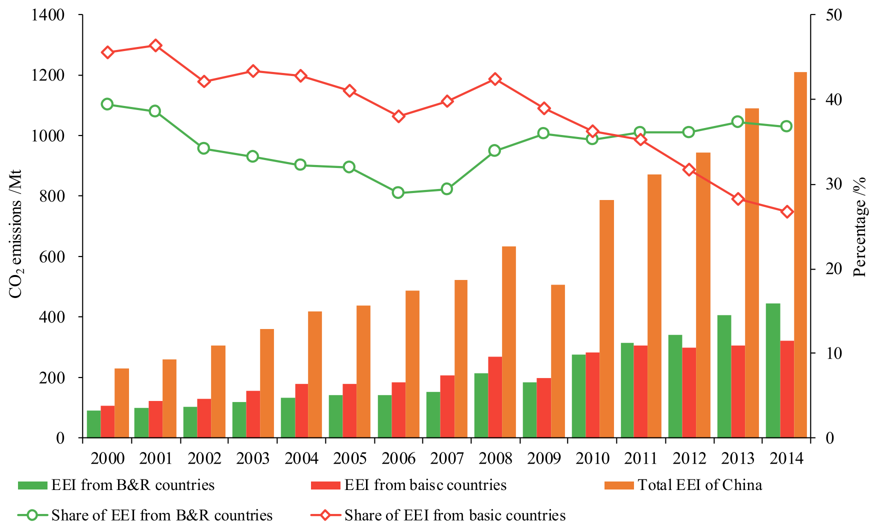

Fig. 4. CO_2 emissions embodied in China's imports from 2000 to 2014.

tries was not significant before 2008 and tended to be stable after 2010. The proportion of EEI from basic countries declined dramatically to 26.7% in 2014 from 45.6% in 2008. Comparison with 48%–60% of the import volume, the proportion of EEI from basic countries was much lower. The main reason for this phenomenon is that most of the 38 basic countries are developed countries such as OECD countries, and their advanced production technology and low-emission energy structure guarantee lower CO_2 emissions embodied in China's unit import from basic countries. The historical trend of EEI from B&R countries was upward except 2009. It increased from 90.7 Mt in 2000 to 444.7 Mt in 2014, and exceeded the EEI from basic countries in 2011. The share of EEI from B&R countries maintained at around 36% after 2008. The different trends of EEI between basic countries and B&R countries indicated that B&R countries produced large amounts of CO_2 emissions due to the location transfer of China's exports to its neighboring regions, especially the developing and less developed regions as mentioned above.

As shown in Fig. 5, the major four sectors of EEI are Mining (S02), Chemical Products (S08), Basic Metals and Fabricated Metal Products (S11), Electronic and Electrical Equipment (S13). Among them, the sector of Mining (S02) had the largest increase due to the average annual growth rate of 21.0%. Its EEI reached to 426.4 Mt in 2014, accounting for 35.2% of the total EEI as the largest sector. In addition, other 6 sectors also increased in varying degrees: Electronic and Electrical Equipment (S13), Transport Equipment (S14), Other Manufacturing and Recycling (S15), Electricity, Gas and Water supply (S16), Travel and Transport (S18), Other Services (S19). The proportions of the other 12 sectors showed declines during the period. China's rapid economic development had led to so large demand of petroleum and mineral resources that it made a 16-fold increase in the import value of Mining (S02). These products were mainly imported from Asian or African regions with relatively low production technology, and meanwhile, mining is a resource-intensive industry whose energy consumption and CO_2 emissions per unit product are generally higher than those of others. As a result, the EEI of Mining (S02) grew at a remarkable rate. In this sense, our results are similar to the paper of Liu et al. (2016) which found that China avoided emissions due to the imports of dirty goods (with higher pollution intensity). The EEI of Other Manufacturing and Recycling (S15) was mainly embodied in luxury industries such as precious stones, precious metals, clocks and watches. The average annual growth rate of Travel and Transport (S18) had also been as high as 22.6% since 2010. The rapid growth of EEI of S15 and S18 are mainly due to the boom of "outbound travels", "overseas online shopping" and "overseas procurement service (Dai Gou)" among China's consumer groups.

5.4. Net CO_2 emissions embodied in China's bilateral trade

The net CO_2 emissions embodied in China's bilateral trade (NEEBT) are equal to the difference between CO_2 emissions embodied in China's exports (EEX) and imports (EEI). The total NEEBT from 2000 to 2014 is shown in Table 3, including basic countries and B&R countries. The NEEBT increased from 346.3 Mt to 1238.7 Mt with the average annual growth rate of 20.0% during 2000 to 2007. After the financial crisis, China's bilateral trade emitted 1676.8 Mt net CO_2 emissions in 2011, the maximum value during the period. And then, the NEEBT continued to decline with the comprehensive effect of the ever-increasing EEI and the slowing down EEX, falling to 1352.2 Mt in 2014. CO_2 emissions embodied in China's exports and imports has attracted attentions from the literature. Pan et al. (2008) found that China's total exports and imports embodied CO_2 emissions of 880 Mt and 257 Mt in 2002. Wei et al. (2011) found the carbon emissions generated for the production of China's exports increased from 979.3 Mt in 2002 to 2633.8 Mt in 2007, and meanwhile, the actual imported carbon emissions to obtain China's domestic consumption were only 231.0 and 376.4 Mt. Liu et al. (2013) found that EEX was about 1101.4 Mt of CO_2 emissions while EEI was about 417.8 Mt in 2002, and they increased to 2968.8 and 824.6 Mt in 2007 respectively. Jiang et al. (2015) found that the CO_2 embodied in China's exports and imports increased from 597 and 164 Mt to 1400 and 235 Mt during 2002 to 2007. Overall, the EEX in the literature mentioned above is about 600∼1100 Mt in 2002 and 1400∼3000 Mt in 2007, while the EEI is about 160∼420 Mt and 230∼830 Mt. The results of this present paper are at a relatively middle location in the above range.

Owing to China's long-term bilateral trade surplus, coal-based energy structure, relatively lower production technology and low-end export structure; the EEX was much higher than the EEI, which made the NEEBT positive through the period. Based on the production-based accounting approach, the bilateral trade made China produce a large amount of CO_2 emissions for other regions. As the NEEBT kept declining after 2011, the impact of the bilateral trade on China's CO_2 emissions begun to weaken. As mentioned above, the EEX of basic countries had been declining since 2011 and meanwhile the increase of its EEI was fairly insignificant. Therefore, the NEEBT of basic countries also showed a downtrend after

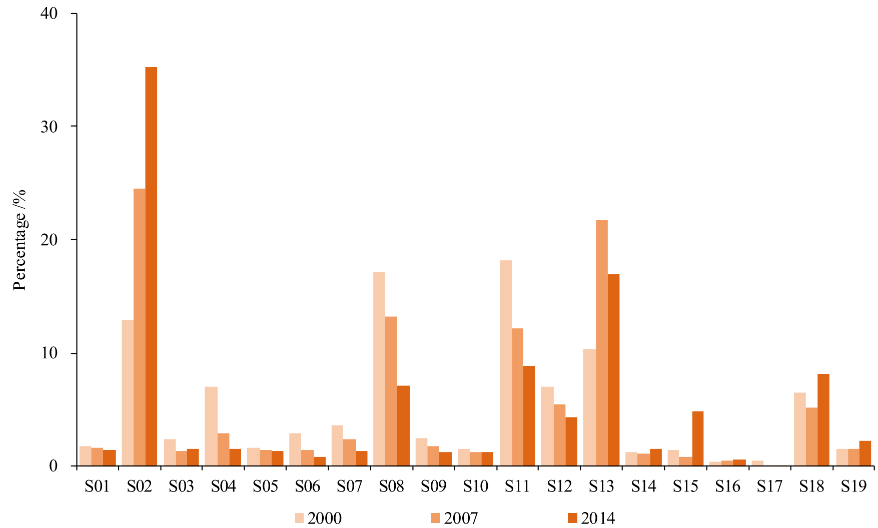

Fig. 5. Industrial structure of CO_2 emissions embodied in China's imports.

Table 3
Net CO_2 emissions embodied in China's bilateral trade from 2000 to 2014.

Year	EEX	EEI	NEEBT	Basic countries			B&R countries		
				EEX	EEI	NEEBT	EEX	EEI	NEEBT
2000	576.7	230.4	346.3	368.2	105.0	263.2	117.9	90.7	27.2
2001	576.5	259.3	317.2	366.5	120.2	246.3	121.5	100.0	21.5
2002	679.1	305.2	373.9	432.7	128.7	304.0	150.0	104.3	45.6
2003	893.6	358.7	534.9	571.6	155.4	416.2	201.5	119.2	82.3
2004	1188.2	417.0	771.3	764.6	178.5	586.2	278.7	134.2	144.6
2005	1433.5	437.9	995.6	926.0	179.7	746.3	350.0	140.0	210.0
2006	1646.8	486.8	1159.9	1056.7	185.3	871.4	429.3	140.7	288.6
2007	1759.8	521.2	1238.7	1112.4	207.0	905.4	516.8	152.6	364.2
2008	1681.1	632.8	1048.2	1048.7	267.9	780.7	536.2	214.6	321.6
2009	1506.1	506.5	999.6	916.7	197.5	719.2	465.3	182.2	283.1
2010	2375.9	763.7	1612.2	1456.7	285.2	1171.4	740.6	277.7	462.9
2011	2549.8	873.0	1676.8	1545.6	307.8	1237.8	824.9	315.3	509.6
2012	2547.8	945.1	1602.6	1475.6	299.2	1176.4	843.6	341.4	502.2
2013	2587.6	1092.4	1495.2	1432.9	308.2	1124.7	886.5	407.7	478.8
2014	2562.7	1210.5	1352.2	1427.9	323.5	1104.4	917.8	444.7	473.1

Note: EEX: CO_2 emissions embodied in China's exports to other countries/regions. EEI: CO_2 emissions embodied in China's imports from other countries/regions. NEEBT: CO_2 emissions embodied in China's bilateral trade with other countries/regions.

2011. It declined to 1104.4 Mt in 2014 – 81.7% of the total NEEBT. The cleaner production technology and energy structure of most basic countries than China were the main reasons for the huge gaps between the EEX and EEI. The difference between export and import structure also made a significant contribution to the gaps. The high proportion of basic countries in the total NEEBT indicated that the surplus CO_2 emissions embodied in China's bilateral trade were mainly caused by the developed regions like OECD countries. The EEX and EEI of B&R countries maintained the upward trend in almost every year except 2009, and the EEX was always higher than the EEI. The NEEBT of B&R countries reached 473.1 Mt in 2014, accounting for 35.0% of the total NEEBT.

15 main countries/regions[3] are selected according to CO_2 emissions embodied in exports and imports between China and them are shown in Fig. 6. The largest EEX was embodied in exports from China to USA, followed by HKG, JPG and KOR, respectively accounting for 17.4%, 14.4%, 8.4% and 5.0% of the accumulative EEX over the period. Meanwhile, China had the largest volume of exports with these four regions. It shows that the export volume is one of the key factors affecting EEX. For EEI, Other Asia had the largest accumulative EEI, followed by KOR, RUS and JPN. China's import volumes from these 4 regions accumulatively ranked the 4 t h, 2nd, 8 t h and 1 st of all 219 trade partners respectively. And among them, China's imports from RUS were less than 18% of those from JPN, but RUS's accumulative EEI was 102.8 Mt higher than JPN's during the period. Besides the import volume, the production technology of partner regions and the import trading structure are also considered as important factors affecting EEI. The accumulative volumes of net CO_2 emissions embodied in China's bilateral trade with USA and HKG were far above other regions, accounting for 25.1% and 21.8% of the total NEEBT respectively. In addition, JPN and DEU also contributed about 10.2% and 4.9%. This further confirms that the surplus of China's embodied CO_2 emissions was mostly transferred from developed countries/regions. As a "world factory", a large amount of CO_2 emissions had been transferred to China by international trade because of China's huge trade surplus with some of the developed countries and the notable gap in production technology. Among the 15 main countries/regions, only ZAF, RUS, AGO and Other Asia had a larger EEI than EEX, from which China's imports are mainly concentrated in energy, mineral recourses and related sec-

[3] These 15 countries/regions are (A-Z) Angola (AGO), Australia (AUS), Germany (DEU), Hong Kong (HKG), India (IND), Japan (JPN), Korea (KOR), Malaysia (MYS), Netherlands (NLD), Other Asia, Russia (RUS), Singapore (SGP), South Africa (ZAF), United Kingdom (GBR) and United States (USA)

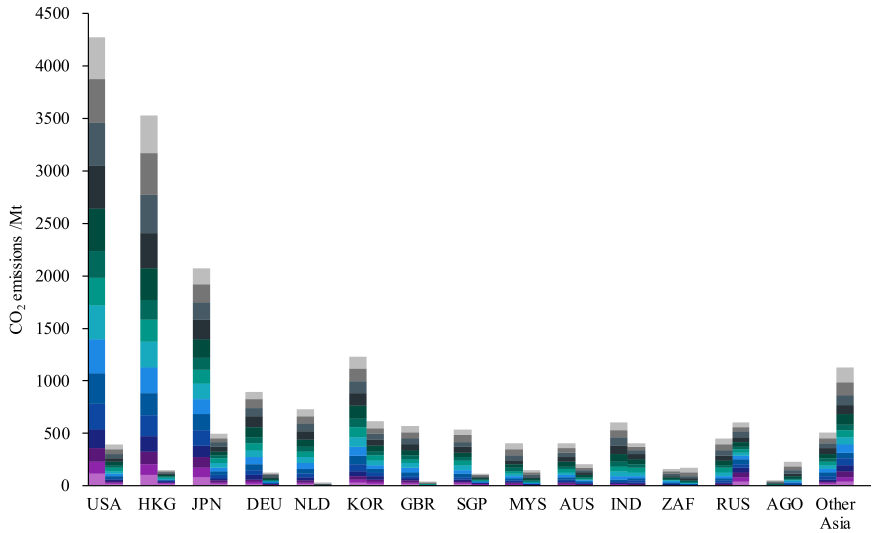

Fig. 6. Net CO_2 emissions embodied in China's bilateral trade with 15 main regions.
Note: The left column of each region is CO_2 emissions embodied in China's exports (EEX) to that region, and the right one is CO_2 emissions embodied in China's imports (EEI) from that region. The blocks in different colors represent 2000–2014 from bottom to top.

Table 4
The impact of China's bilateral trade to global CO_2 emissions from 2000 to 2014.

Year	IEGE	IIGE	IBTGE	Basic countries	B&R countries
2000	381.3	−371.5	9.8	35.6	4.0
2001	349.6	−343.9	5.7	26.0	7.6
2002	415.5	−394.7	20.8	46.1	11.1
2003	591.0	−586.8	4.1	47.7	6.1
2004	833.2	−815.6	17.6	76.5	8.4
2005	1029.3	−938.0	91.3	158.3	13.9
2006	1161.0	−997.4	163.7	219.8	44.2
2007	1209.2	−1024.9	184.3	231.7	80.4
2008	1017.0	−864.7	152.3	197.7	72.5
2009	1008.3	−927.9	80.4	112.1	47.4
2010	1628.2	−1592.6	35.7	154.1	54.2
2011	1710.8	−1702.3	8.5	141.1	38.2
2012	1608.1	−1562.5	45.6	141.0	17.1
2013	1460.6	−1405.7	54.9	120.4	−5.1
2014	1275.0	−1133.3	141.7	152.6	1.4

Note: IEGE is the impact of China's exports on global CO_2 emissions; IIGE is the impact of China's imports on global CO_2 emissions; IBTGE represents the contribution of China's bilateral trade to global CO_2 emissions.

tors. Imports from those 4 countries not only met China's domestic needs, but also avoided more CO_2 emissions for China.

6. Impact of China's bilateral trade on global CO_2 emissions

Under the assumption of non-trade scenario, the impact of China's exports and imports on global CO_2 emissions (IEGE and IIGE) can be calculated according to Eq. (9) and (11). Adding them, we can get the impact of China's bilateral trade on global CO_2 emissions (IBTGE) as shown in Table 4. During the period, all of the IEGE were positive while those of imports were negative. The export trade created many job opportunities domestically, stimulated China's economic development and avoided a large amount of CO_2 emissions for other regions from the production-based perspective. But it increased global CO_2 emissions under the assumption of non-trade scenario, in other words, global CO_2 emissions were increased when the trade partners imported China's products to reduce their domestic CO_2 emissions. The IEGE had weakened since 2011 due to China's declining carbon emission intensity and the optimized export structure. The import trade avoided CO_2 emissions domestically in China, and also reduced global CO_2 emissions. The impact of China's exports was quantitatively opposite to that of imports, and their absolute values and variation trends are fairly close. Like the IEGE, the IIGE (absolute value) began to decrease after 2011. The main reason was that the regions China imported mining products from were mostly Asian and African developed countries, whose carbon emission intensities were basically equivalent to those of China and advantages of production technology were not obvious, and therefore the global CO_2 emission reduction caused by imports decreased. The combined contribution of China's exports and imports to global CO_2 emissions was always a positive but extremely low number, meaning that China's bilateral trade partly increased global CO_2 emissions. The IBTGE grew from 17.6 Mt in 2004 to 184.3 Mt in 2007. It fell to 8.5 Mt in 2011, and then increased to 141.7 Mt again in 2014. During the period, the largest increase of global CO_2 emissions accounted for about 3.3% of China's production-based CO_2 emissions in 2007, and the smallest accounted for only 0.1% in 2011. The contribution of the bilateral trade between China and basic countries were higher than the total impact, with a maximum gap of 132.6 Mt (2011) during the period. It reveals that the bilateral trade between China and the ROW offset the increase of global CO_2 emissions caused by the bilateral trade between China and basic countries. China's bilateral trade with B&R countries also slightly increased global CO_2 emissions in most years. Specially, the bilateral trade between China and B&R countries reduced global CO_2 emissions by 5.1 Mt in 2013. It shows that the international trade can not only meet the demands of China's own economic development, but also contribute to global carbon emission reduction on the premise of reasonable trade location choice and optimized industrial structure in the context of globalization.

The contribution of China's bilateral trade with 15 main regions to global CO_2 emissions is shown in Fig. 7. China's exports to USA had the greatest impact on global CO_2 emissions, accumulatively increasing 3413.6 Mt of global CO_2 emissions, followed by JPN (1685.0 Mt) and HKG (1505.4 Mt). China's imports from JPN made the largest reduction of global CO_2 emissions, followed by KOR and USA. They had accumulatively reduced 2371.8, 1632.8 and 1347.1 Mt of global CO_2 emissions over the period respectively. As shown in the figure, both China's exports and imports with developed countries/regions had a larger impact than that with other developing countries/regions. And under the assumption of non-trade scenario, the main reason for this distribution is obviously that there were significant gaps in production technology between

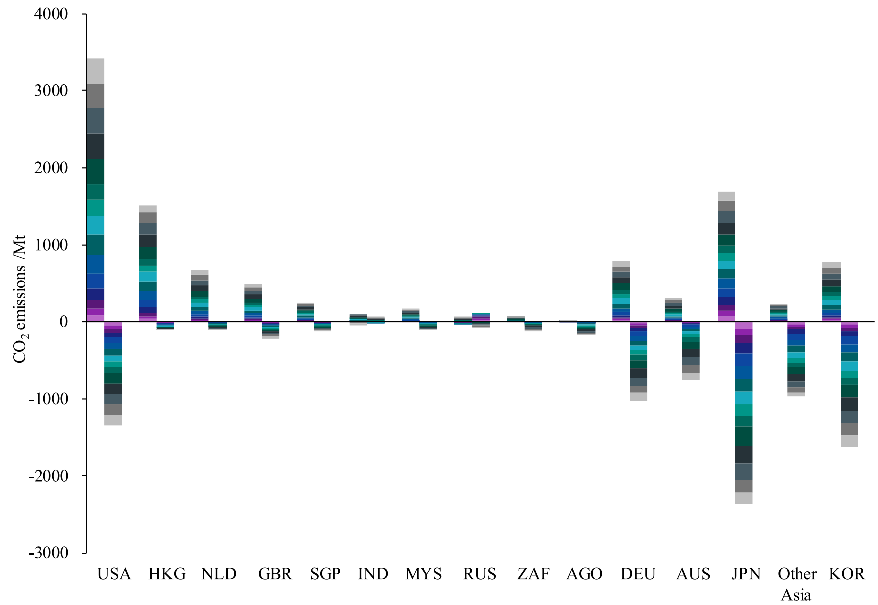

Fig. 7. The impact of China's bilateral trade with 15 main regions on global CO_2 emissions.
Note: The left column of each region is the impact of China's exports to that region on global CO_2 emissions, and the right one is the impact of China's imports. The blocks in different colors represent 2000–2014 from bottom to top.

China and developed countries/regions. Due to those gaps, China's imports from developed countries/regions reduced a large amount of global CO_2 emissions although China's exports increased global CO_2 emissions on the contrary. Together, China's bilateral trade with USA increased the largest accumulative amount of global CO_2 emissions by 2066.4 Mt, HKG and NLD also increased 1400.3 and 556.4 Mt, while China's bilateral trade with KOR, Other Asia and JPN made a reduction of 859.9, 731.0 and 686.7 Mt respectively. For IND, MYS, RUS and other developing countries, although China's bilateral trade volume with these countries was very large, their IBTGE were negligible because their production technology and energy efficiency were virtually equal to those of China. The results also indicated that the bilateral trade between China and B&R countries would make little difference on global CO_2 emissions while the economies of all countries along the B&R routes could be promoted by the bilateral trade with China.

7. Main conclusions and findings

In the process of economic globalization, the export trade has led to the rapid growth of China's economy, and also has brought great pressure on China's resources and environment. Under the CO_2 emission constraint based on the production-based accounting approach, developed countries transferred large amounts of CO_2 emissions to China through the international trade. The EEI had become considerable since 2011 because the growth rate of China's imports exceeded its exports and the structure of China's imports changed a lot as well. Based on the EEBT model, we calculated CO_2 emissions embodied in China's bilateral trade with 219 countries/regions using the SRIO model with non-competitive imports. The estimation results show that China's EEX increased from 576.7 Mt in 2000 to 2562.7 Mt in 2014, accounting for 19.9% and 23.1% of China's production-based CO_2 emissions respectively. China's ever-increasing exports after 2011 failed to cause an overgrowth of EEX due to the nationwide mandatory emission reduction obligation. In addition, the transformation of China's export trade structure from traditional resource-intensive and labor-intensive sectors to capital-intensive and technology-intensive sectors played a positive role in the sluggish growth of EEX. And meanwhile, China's EEI increased from 230.4 Mt in 2000 to 1210.5 Mt in2014 with a little higher growth rate than that of EEX. The analysis of the location distribution and industrial structure of China's imports suggests that China had been transferring more and more CO_2 emissions to the ROW through importing large amounts of energy and mineral resources. The CO_2 emissions embodied in luxury industries and caused by overseas shopping should not be ignored. Subtracting EEI from EEX, the net CO_2 emissions embodied in China's bilateral trade was invariably positive in 2000–2014, that is, the international trade made China produce a large amount of CO_2 emissions for other regions, especially for OECD countries.

At last, the impact of China's bilateral trade on global carbon emissions was analyzed under the assumption of non-trade scenario. It is indicated that China's exports increased global CO_2 emissions while the imports reduced them. And the combined results show that China's bilateral trade increased global CO_2 emissions by an extremely low degree. It should be pointed out that, China could contribute to reducing global CO_2 emissions through the international trade according to the impact of China's bilateral trade with B&R countries to global CO_2 emissions. Our study suggests that China should reduce CO_2 emissions embodied in its exports to decrease the impact on global CO_2 emissions. For example, China should continue to optimize the export structure, increase the share of low-carbon products in total exports, limit the export of high energy consumption and high emission products, improve efficiency in energy consumption, support the development of clean and renewable energies, reduce the proportion of fossil energy in the present energy consumption. And China should also strengthen the carbon emission verification and upgrade the emission access threshold of its imports, which could help China maintain and expand the contribution to global carbon emission reduction.

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